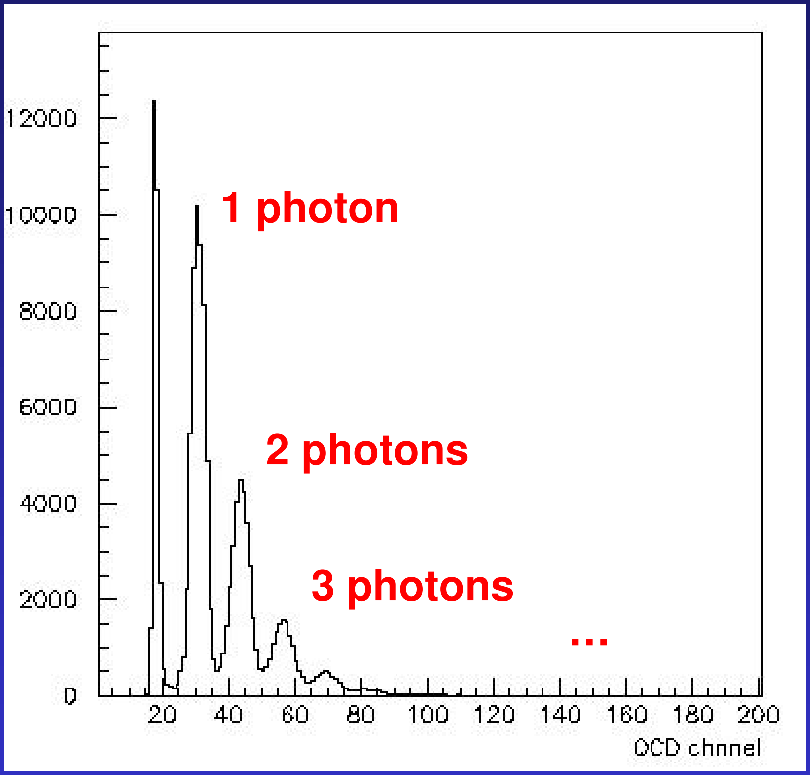
Silicon Photomultiplier: Physics, Development and Applications

V.Saveliev,

Obninsk State University, Russia

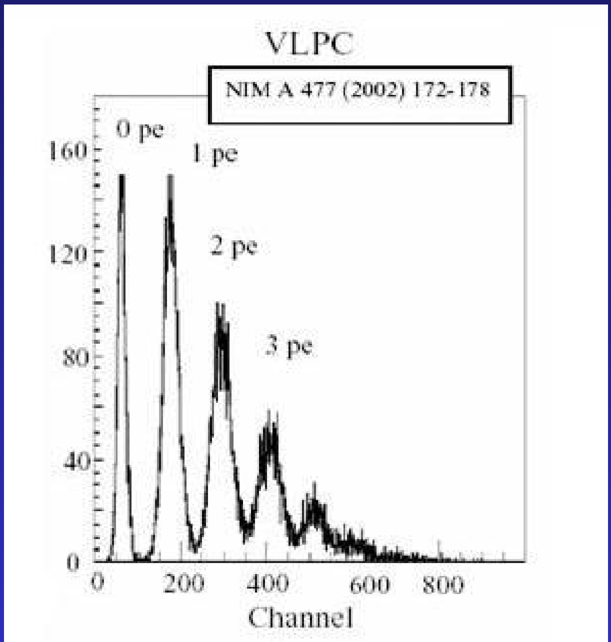
19.May.2006

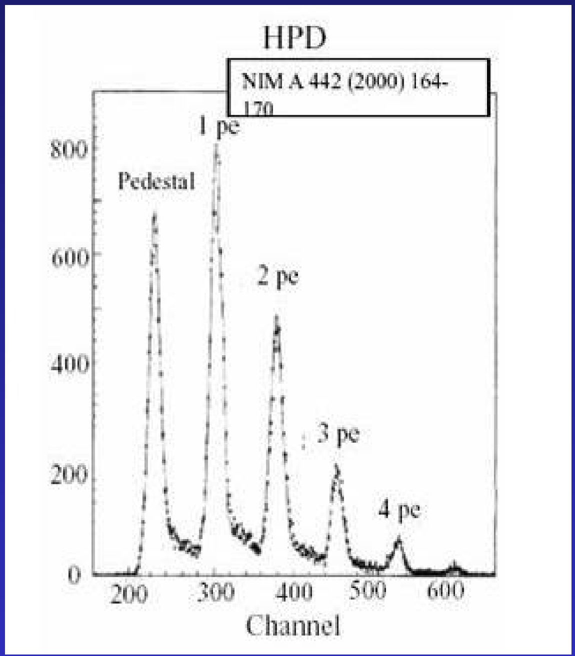
Silicon Photomultiplier

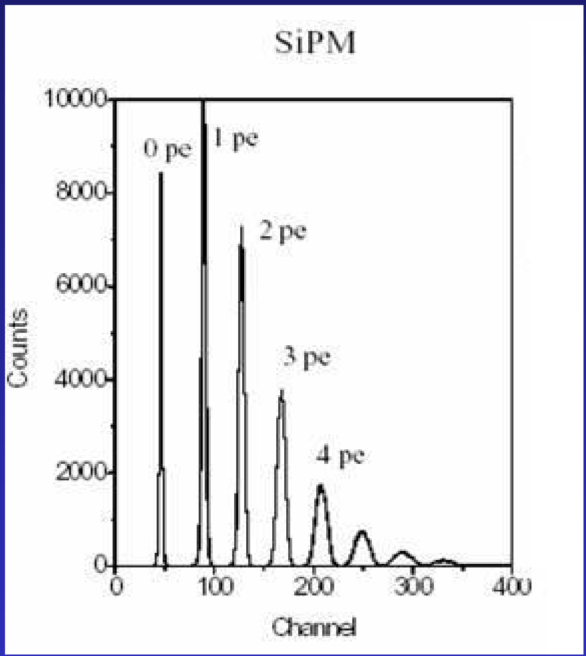


Novel type of PhotoSensor

Single Photon Detection Performance





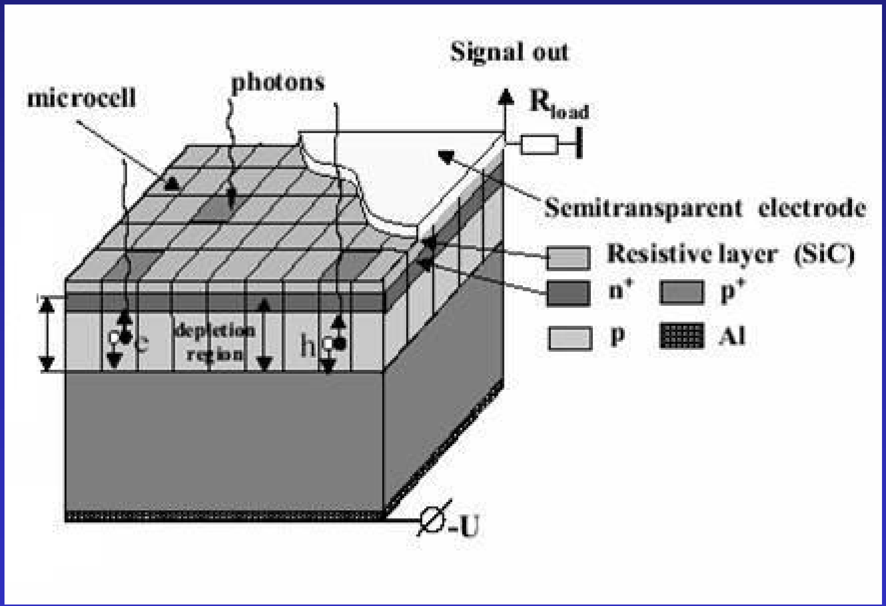


Silicon Photomultiplier

- Detection efficiency ~25%-40%
- Single photon performance (Intrinsic Gain ~10^6),
- Proportional mode for the photon flux (large dynamic range),
- Operation conditions:
  - Low Operational Voltage ~50-60 V,
  - Room Temperature,
  - Non Sensitive to Magnetic Field,
  - Minimum Required Electronics,
- Miniature size and possibility to combine in matrix.
- Low cost (in mass production conditions)

Silicon Photomultiplier Structure

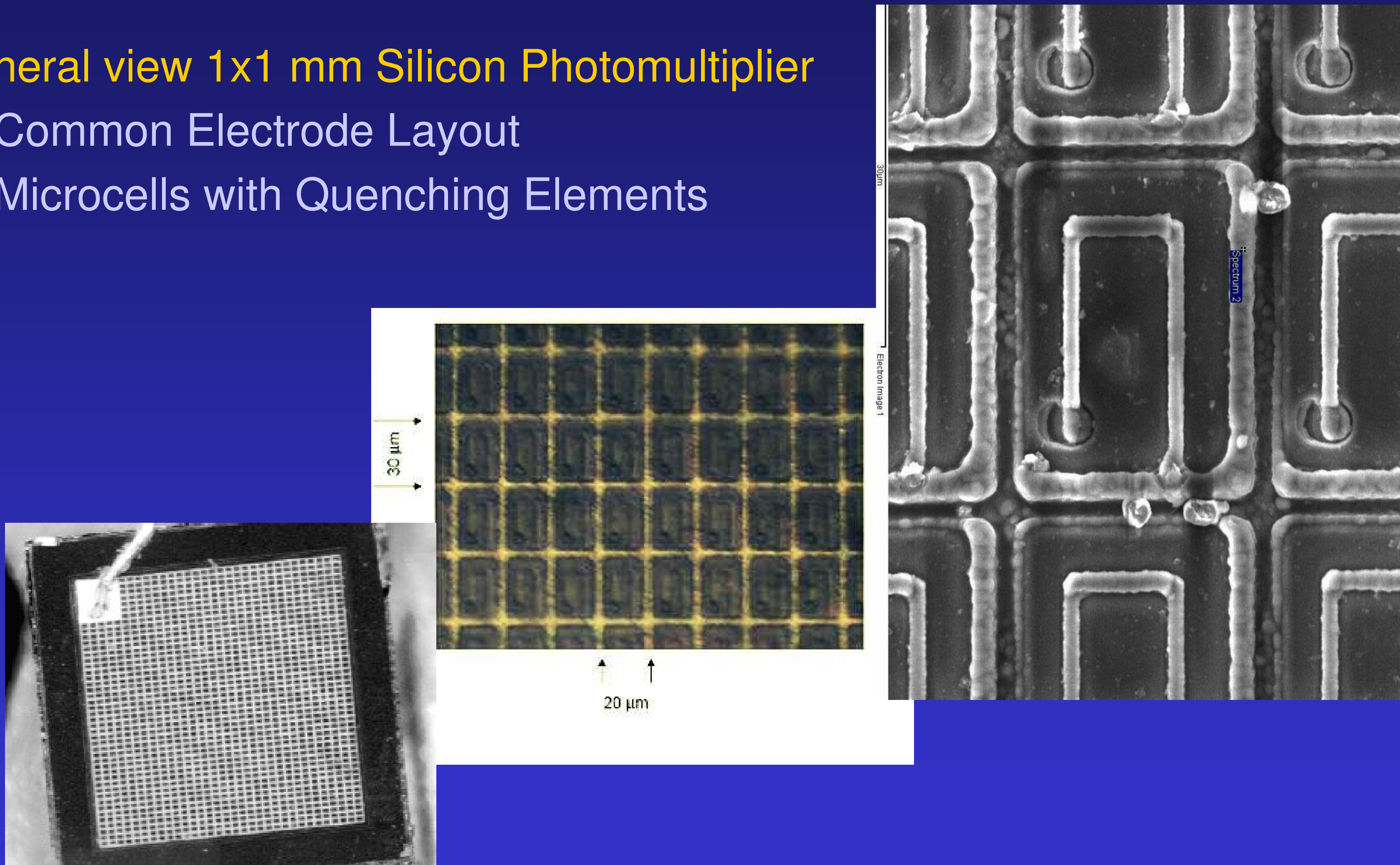
- Silicon fine Micro Cells Structure on common substrate
- Breakdown Mode Operation of Micro Cells.
- Integrated Quenching Mechanism
- Common Output



Silicon Photomultiplier Structure

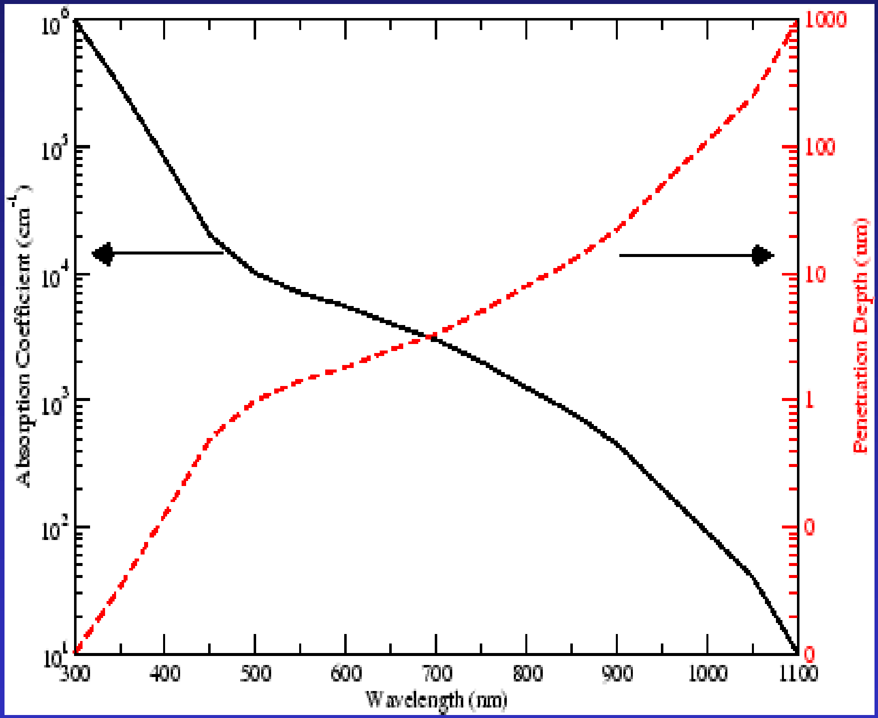
General view 1x1 mm Silicon Photomultiplier

- Common Electrode Layout
- Microcells with Quenching Elements



Detection Efficiency

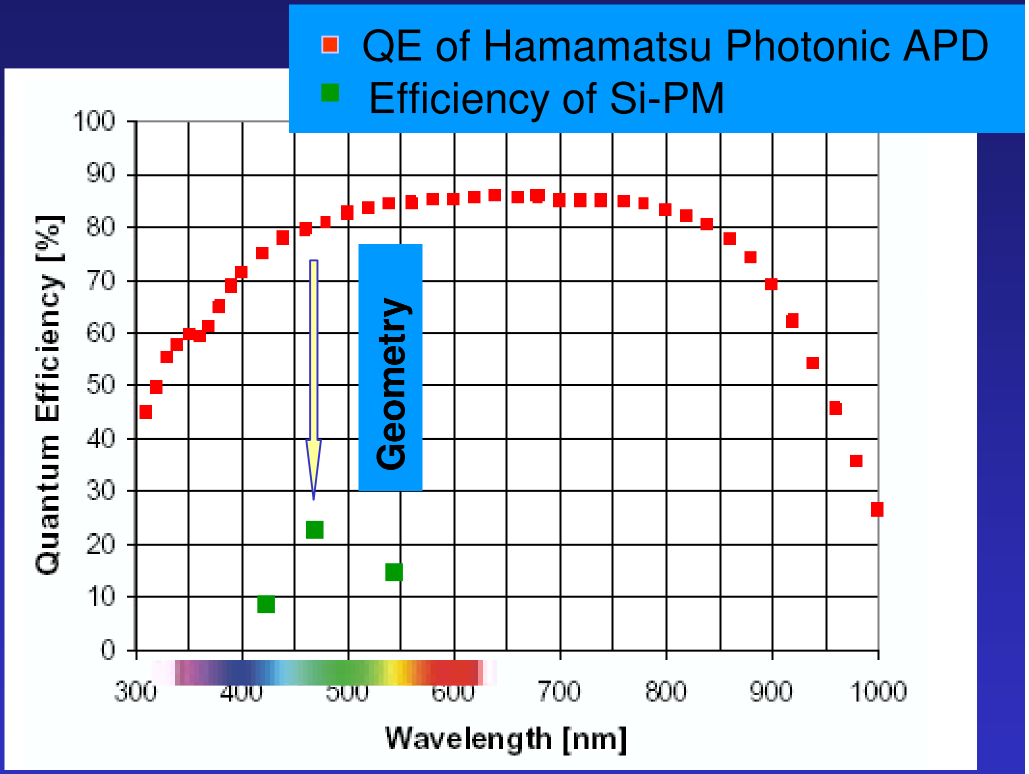
- Quantum Efficiency of Microcell
  – wavelength and optical absorption function dependent,
- Geometry Efficiency
  – the technology topology gives the limitation of the sensitive area (sensitive area is microcells)
- Breakdowm Mode is statistical process
  – probability that photoelectron will triggered an avalanche process in Si



The Depletion Area is ~5 μm: Low Resistive Si, Low Biase Voltage

Detection Efficiency

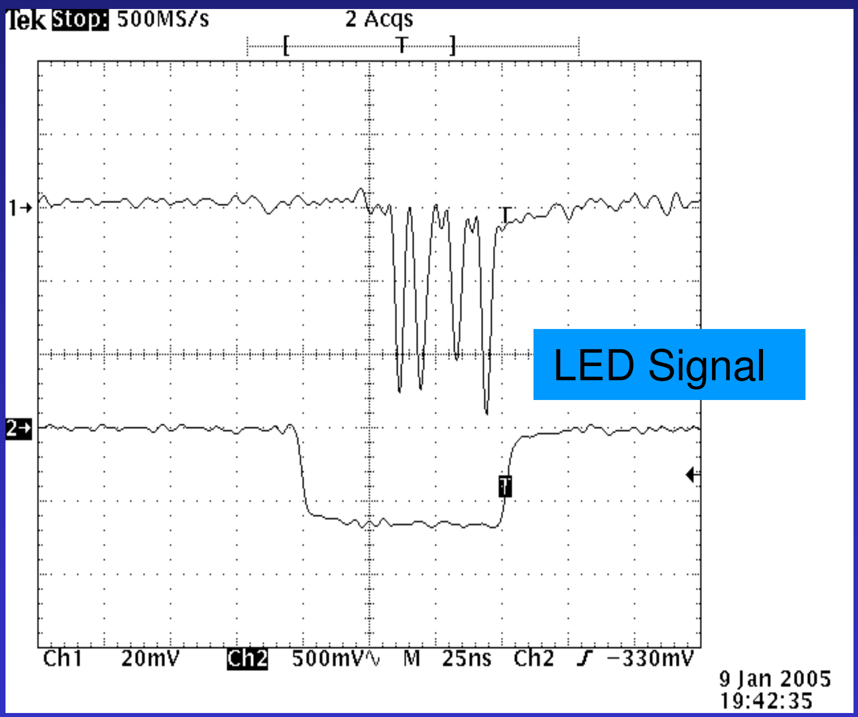
- UV region of Light
  - Is limited by present technology topology (dead layer on the top),
- IR region of Light
  - Is limited by thikness of sensitive layer,
- Absolute Value Scaling
  - Is Geometry filling factor

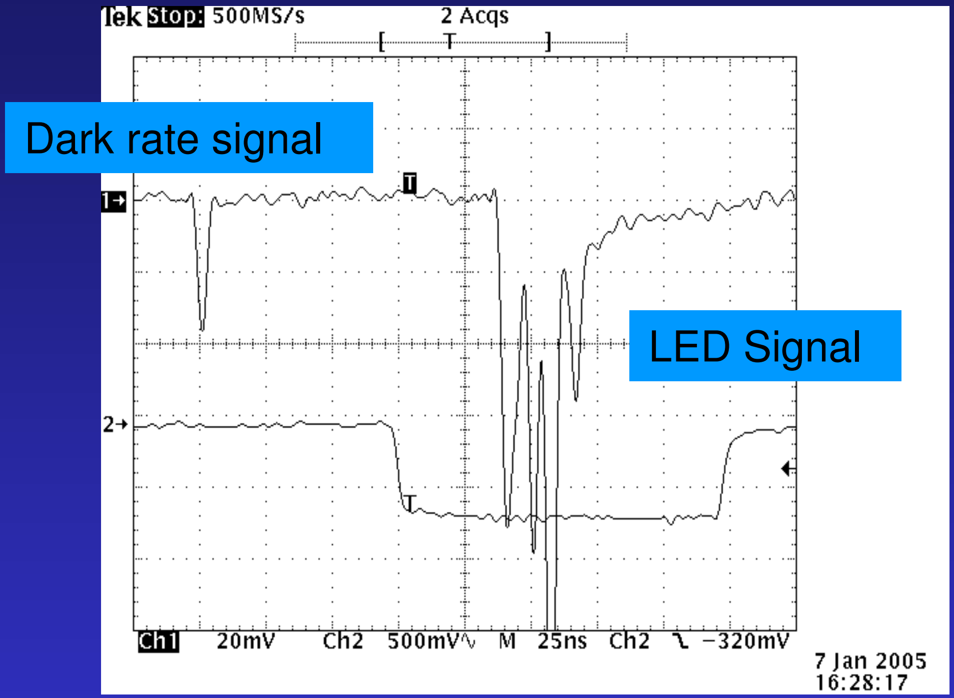


The Si-PM has green light sensitivity and
Total Detection Efficiency for green range of light is ~25%

Silicon Photomultiplier Performance

- Signal of Silicon Photomultiplier with preamplifier (Gain 20)

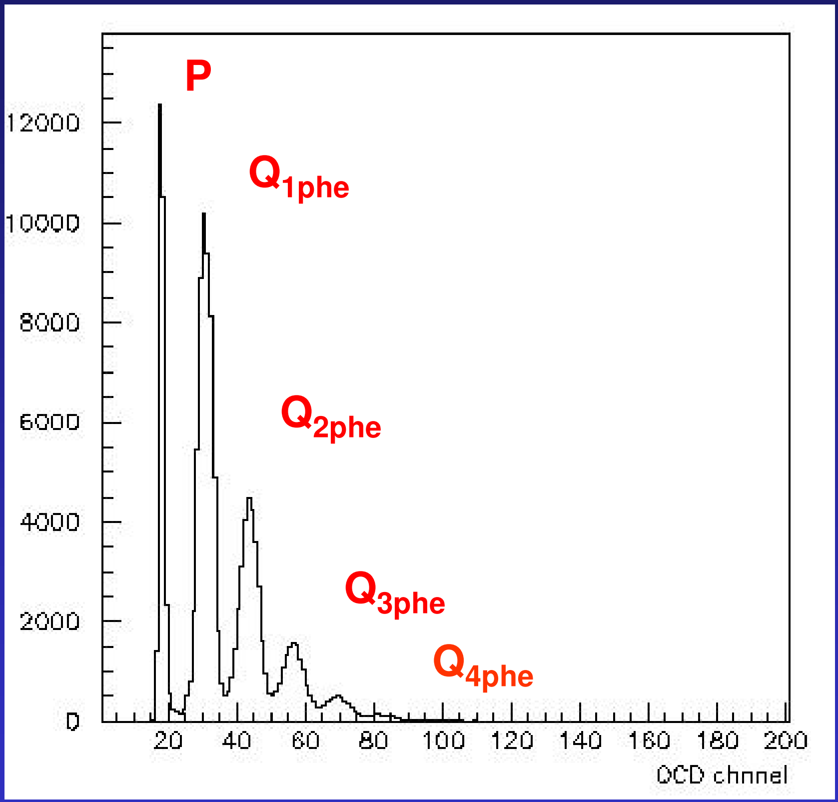




Signal of Silicon Photomultiplier can be readout without Frontend Electronics

Silicon Photomultiplier Performance

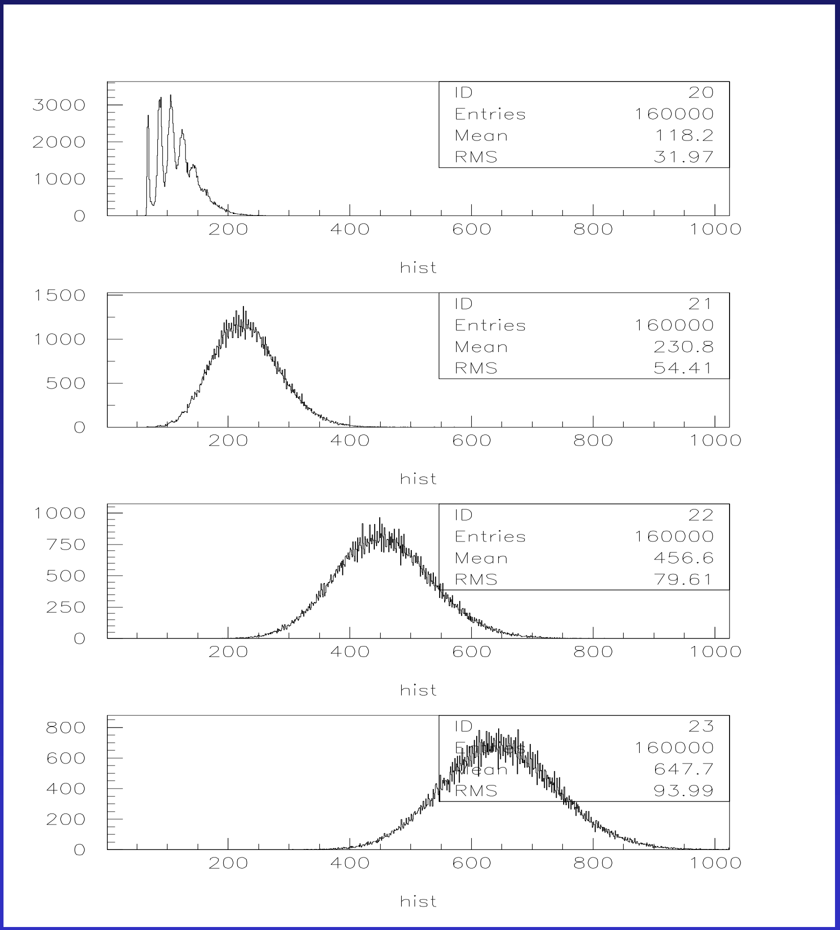
- Single Photon Detection
  - High intrinsic Gain of amplification ~10^6 and
  - very high Identity of microcells (the width of 1st phe peak is the defined by distribution of signals from 1500 microcells which detects single photons randomly distributed across the area of Si-PM)



Silicon Photomultiplier has the possibility Detect up to single Photon

Silicon Photomultiplier Performance

- Dynamic Range
  - Defined by fine structure of Silicon Photomultiplier – number of microcells (~1500),
- Linearity
  - Intrinsic linearity of Silicon photomultiplier is very high, differential nonlinearity on the level 20% of single photon responce

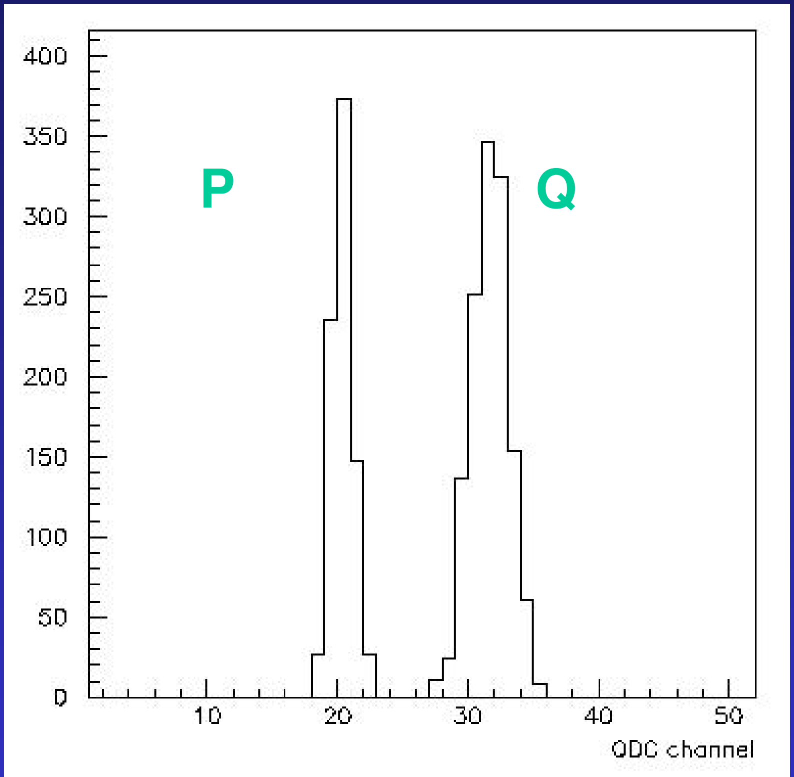


Statistical character of the photons detections gives the nonlinearity, which can be correct by statistical function

Silicon Photomultiplier Performance

- Resolution of single microcell

$$\frac{\sigma}{A} \approx 7.8\%$$



Single Microcell of SiPM – size 20x30 microns (Single Photon Avalanche Counter with Integrated Quenching Element)

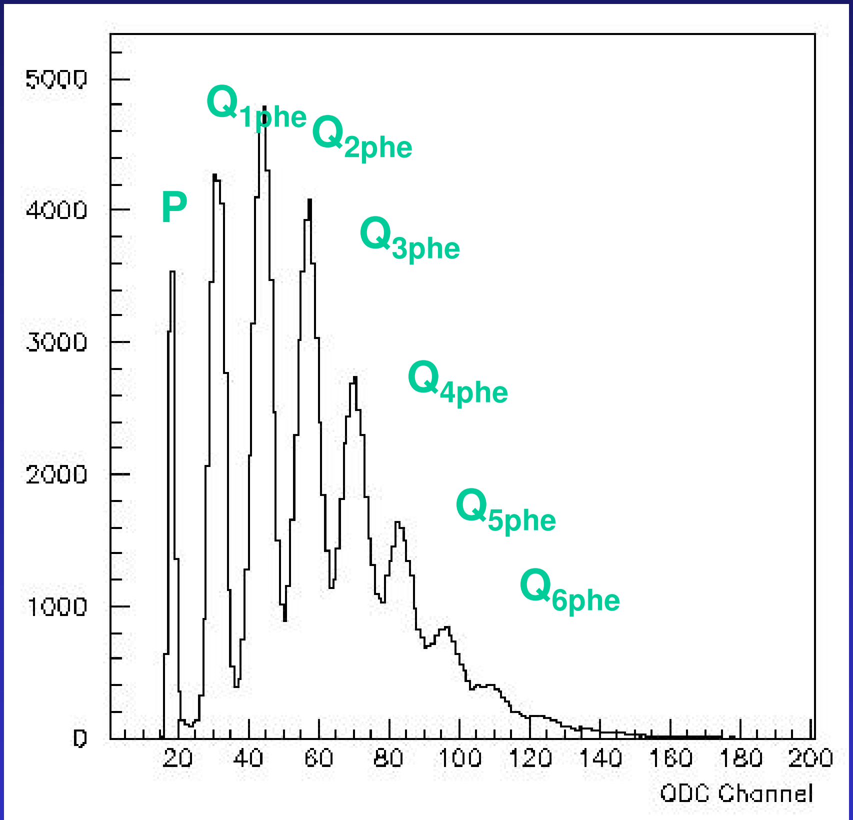
Silicon Photomultiplier Performance

- Resolution of
  Silicon photomultiplier

$$A_N = N \times A_{1phe}$$

$$\sigma_N = \sqrt{N}\sigma_{1phe}$$

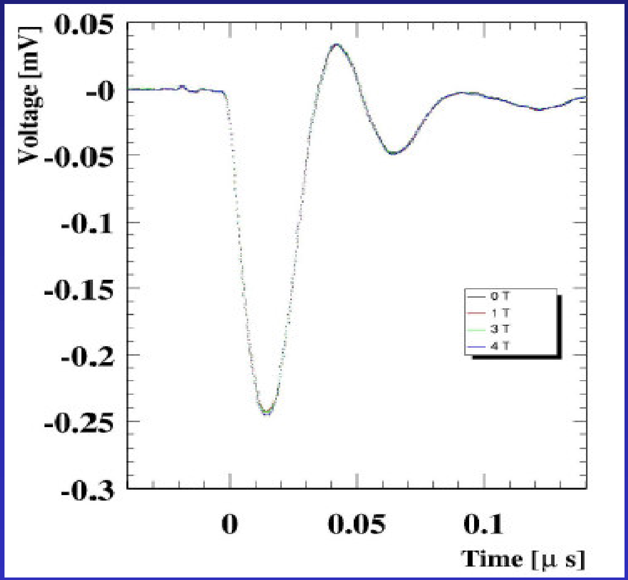
$$\frac{1}{\sqrt{N}}\frac{\sigma_{1phe}}{A_{1phe}}$$

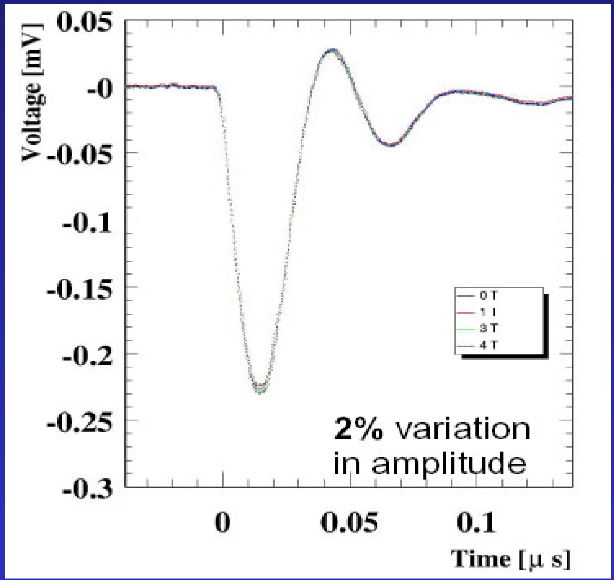


Full Size Silicon Photomultiplier – 1440 cells (cell - 20x30 microns)
The own Resolution of SiPM is very High (for 100 phe ~ 2 %)
Detection Resolution in Photon Statistic

Silicon Photomultiplier Performance

- Silicon Photomultiplier in Strong Magnetic Field





Test of SiPM in Strong Magnetic Field up to 4 Tesla (Amplitude of SiPM signal in magnetic field with different orientations) (CALICE Meeting, DESY, 30.01.2004)

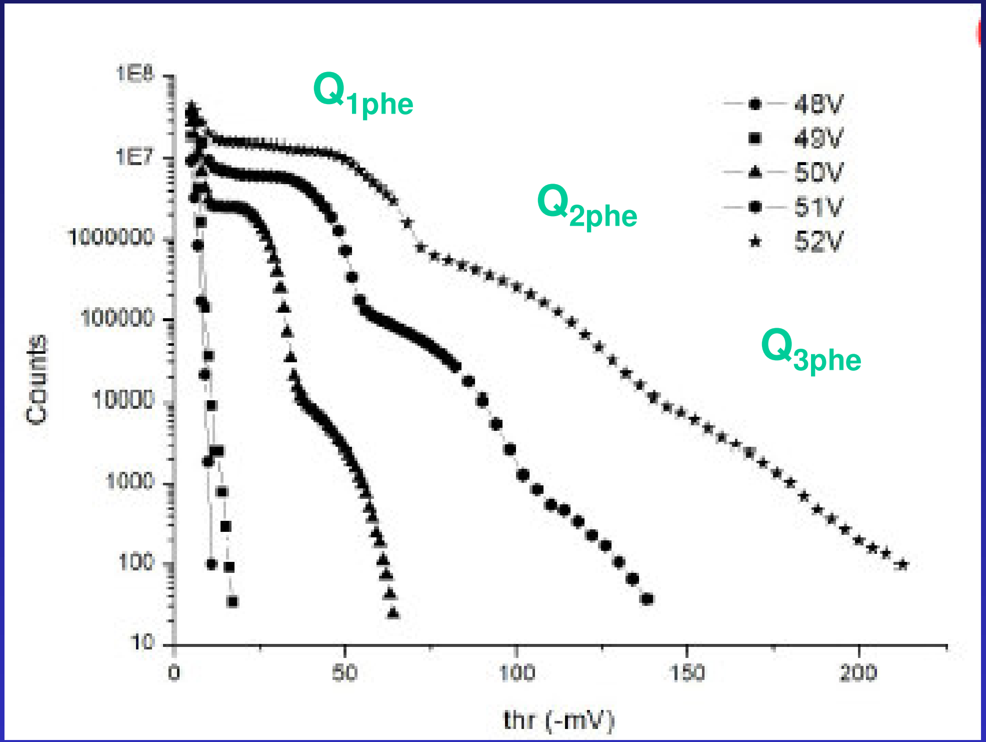
Silicon Photomultiplier Performance

- Dark Count Rate
  - Probability that a bulk thermal electrons will trigger an avalanche process (Voltage Dependent) - characterized by frequency,
- Dark Count Rate Signal Amplitude
  - is amplitude of single photoelectron (cells signal)

Typical value of Dark Rate is 0.6 MHz for 1 mm2 of Si-PM (~1500 cells), depleted layer 5 microns (CPTA)

Silicon Photomultiplier Performance

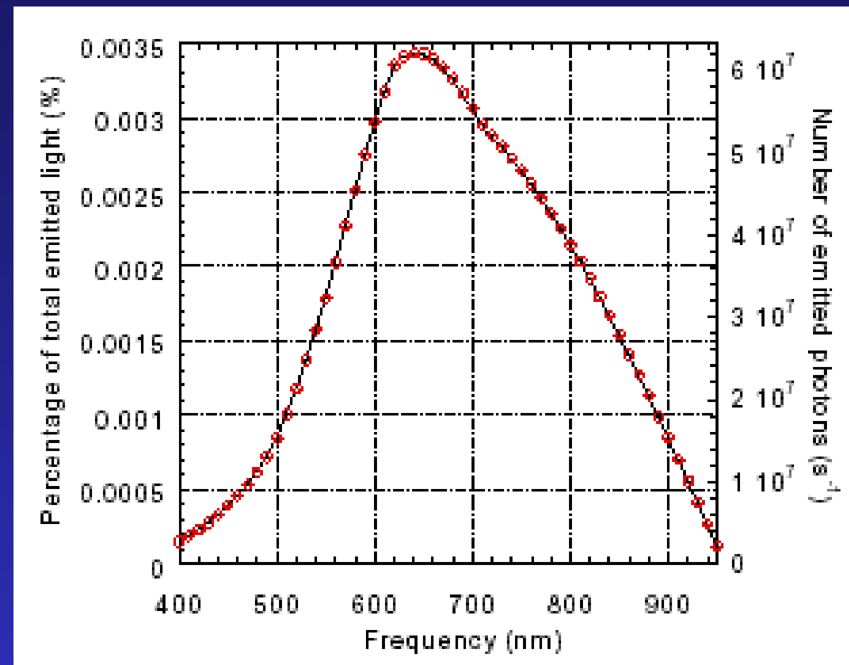
- Dark Count Rate as a function of the Applied Biase

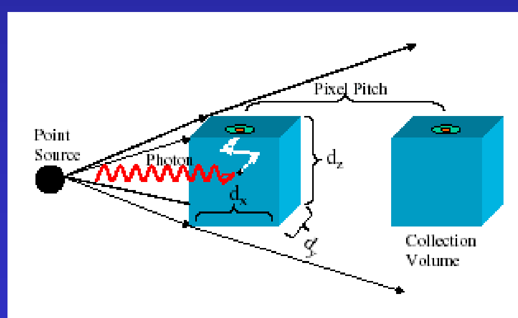


Dark Count Rate is significant limitation for the Single Photon Detection Mode, For the measurement of Photons Flux on the level more than ~ 4-5 photoelectrons this factor is negligible, because the amplitudes of Dark Rate Signal is equivalent of Single Photoelectron Signal

Silicon Photomultiplier Performance

- Optic Crosstalk
  - During avalanche breakdown a cells emits a photons. These photons should not reach the other cells of the SiPM because this would result in the initiation of breakdown in those cells – Optical Crosstalk.





Spectrum of Emited Photons during the Avalanche process in Si

It is necessary Special Technology (Trench Technology) for preventing Optical Crosstalk (for now only one type of SiPM has such techniology)

Silicon Photomultiplier Applications

- DESY International LInear Collider Group, in particularly Hadron Calorimeter Activity – is leader in Testing of SiPM, few groups from US, Fermilab, SLAC started, Japan few groups started test of SiPM...
- Pisa University is good progress in Understanding of SiPM for Medical Application, - especially Positron Emission Tomography Application
- Regina University (Canada) in connection to the Jef Lab, Scintillator Fiber Calorimeter, GlueX experiment.
- Cosmic Research Activity, MPI, Russia, AMS experiment
- Cherenkov Detectors (necessary get good single photon detection performance)
- Exotic Applications, PSI, Liquid Xenon Calorimeter

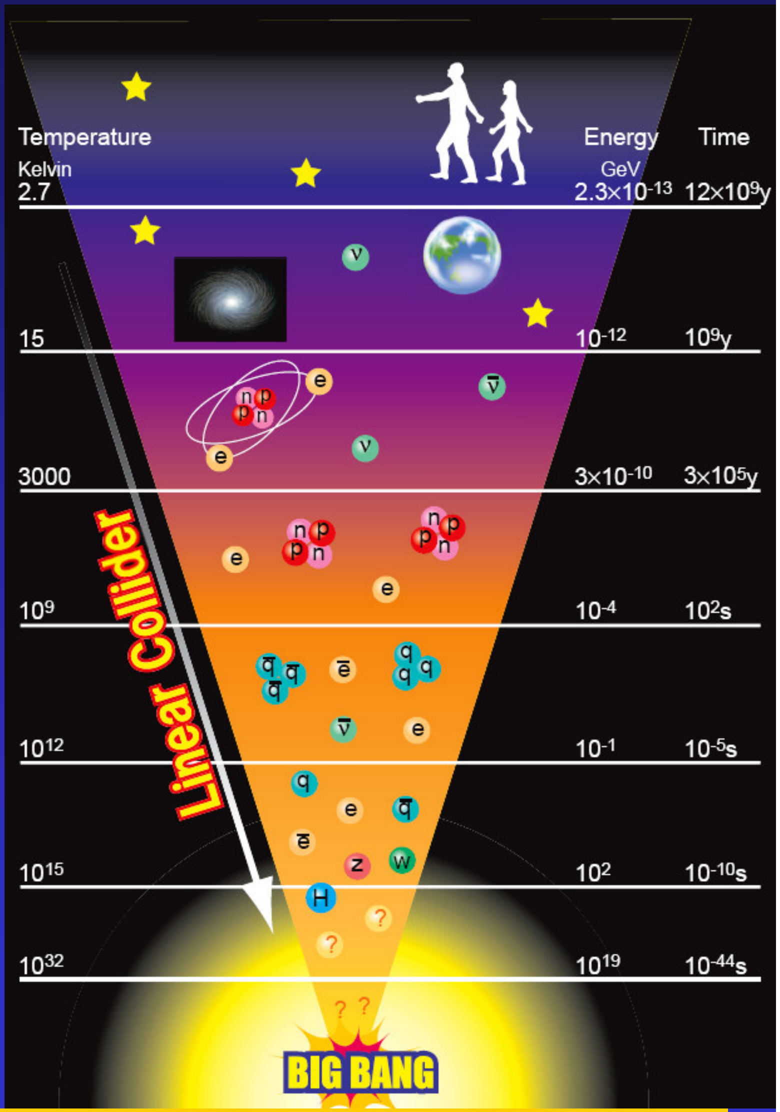
Silicon Photomultiplier became wide used in different applications

The Terascale Terrain

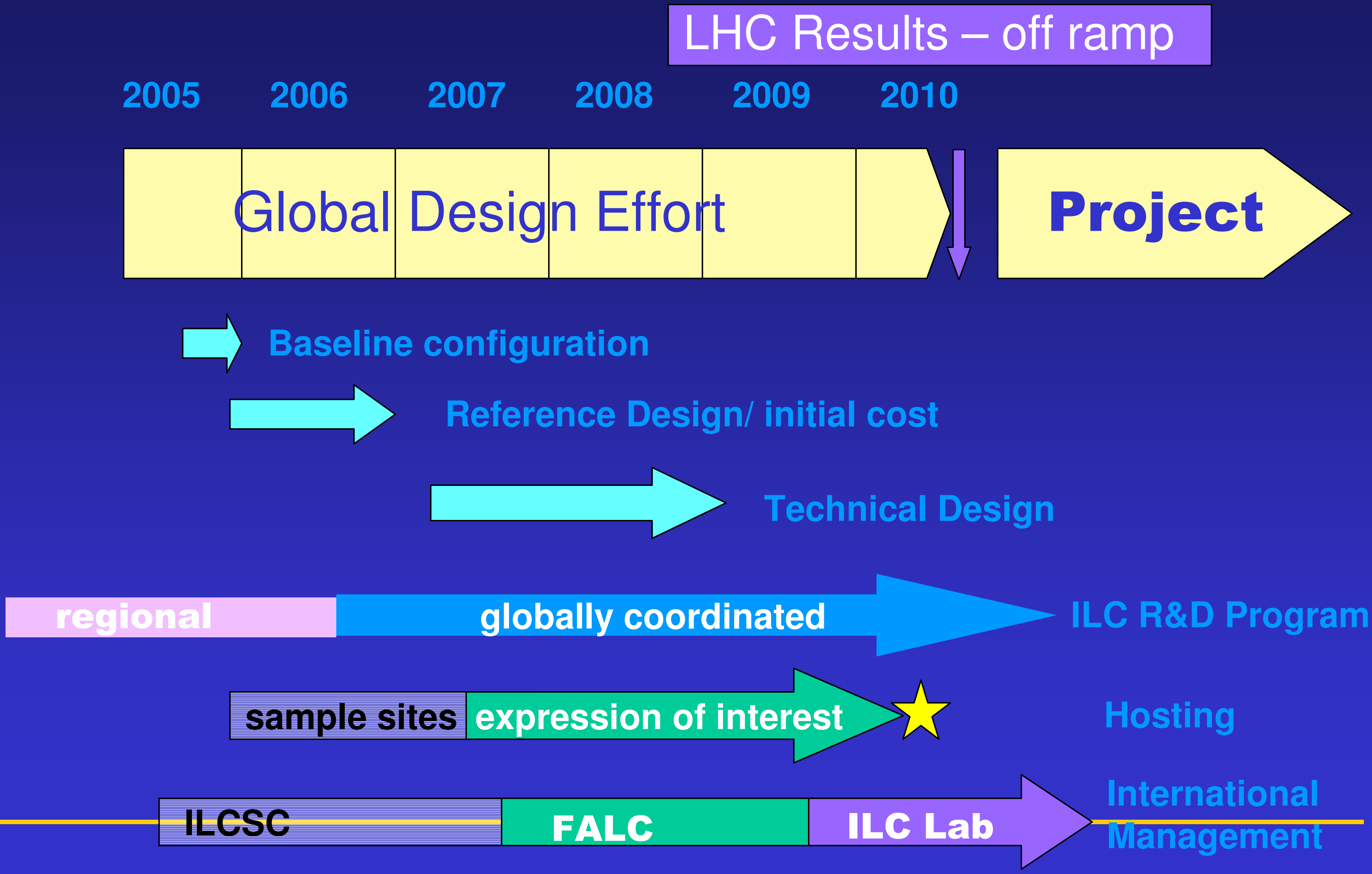
Increasing energy of particle collisions in accelerators corresponds to earlier times in the universe, when phase transitions from symmetry to asymmetry occurred, and structures like protons, nuclei and atoms formed.

The Terascale (Trillion electron volts), corresponding to 1 picosecond after the Big Bang, is special. We expect dramatic new discoveries there.

The ILC and Large Hadron Collider (LHC) are like telescopes that view the earliest moments of the universe.



The Global Design Effort schedule



ILC layout

2 x 250 GeV linear accelerators for E_{CM} < 500 GeV aimed at 20 mrad crossing angle.

Plan for upgrade to 500 GeV beams (E_{CM} = 1 TeV).

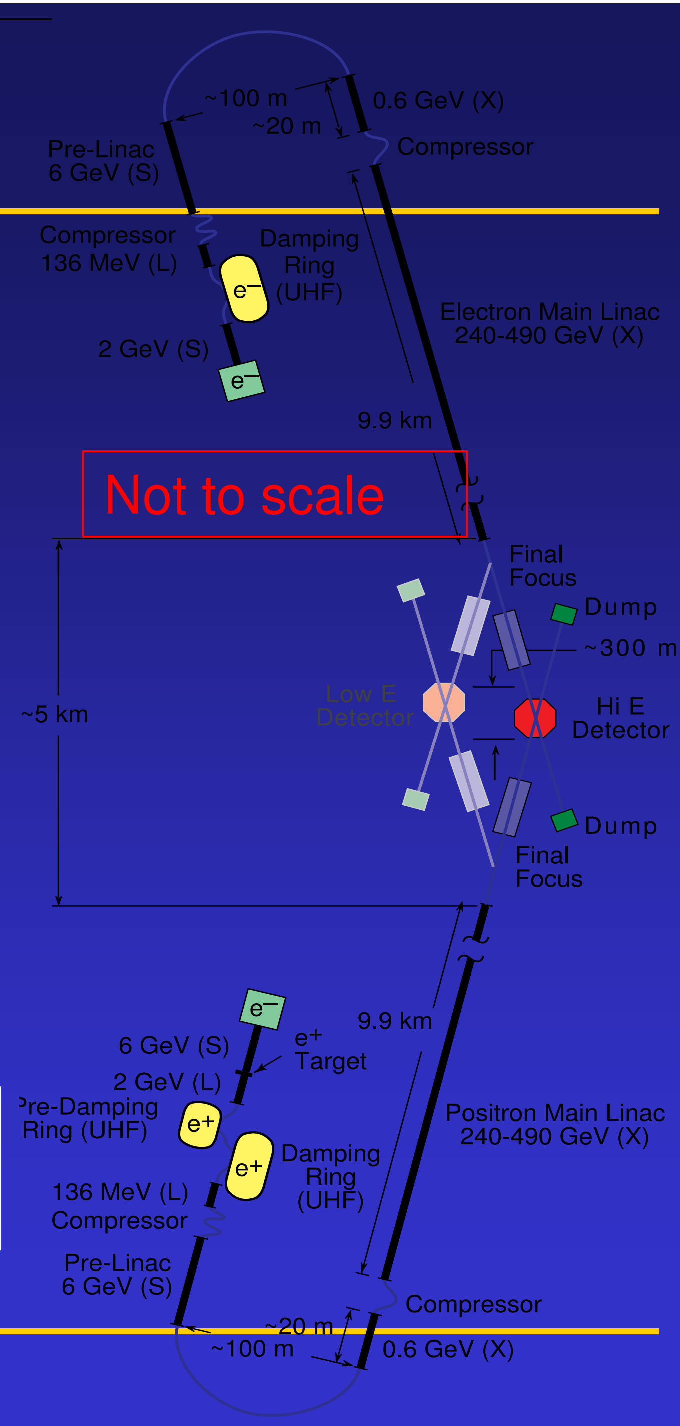
Using backscattered laser light, can produce $\gamma\gamma$ collisions to ~80% of e^+e^- energy.

Positrons made from γ's radiated in undulator (can be polarized) striking a conversion target.

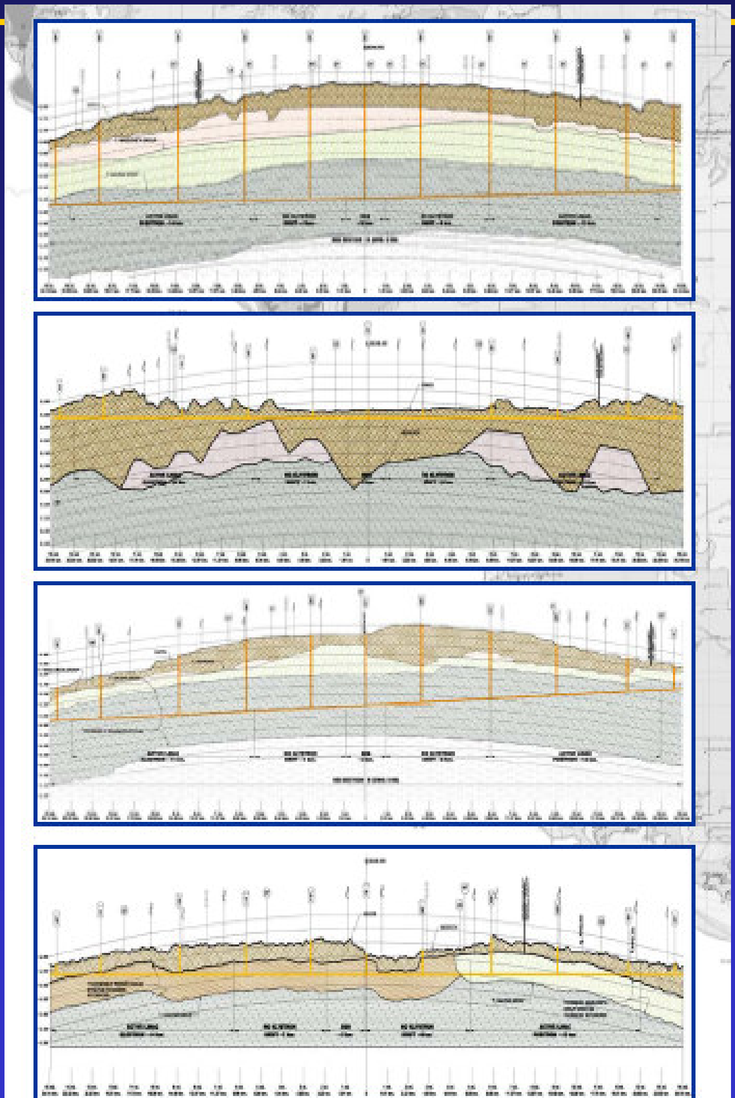
Two interaction points.

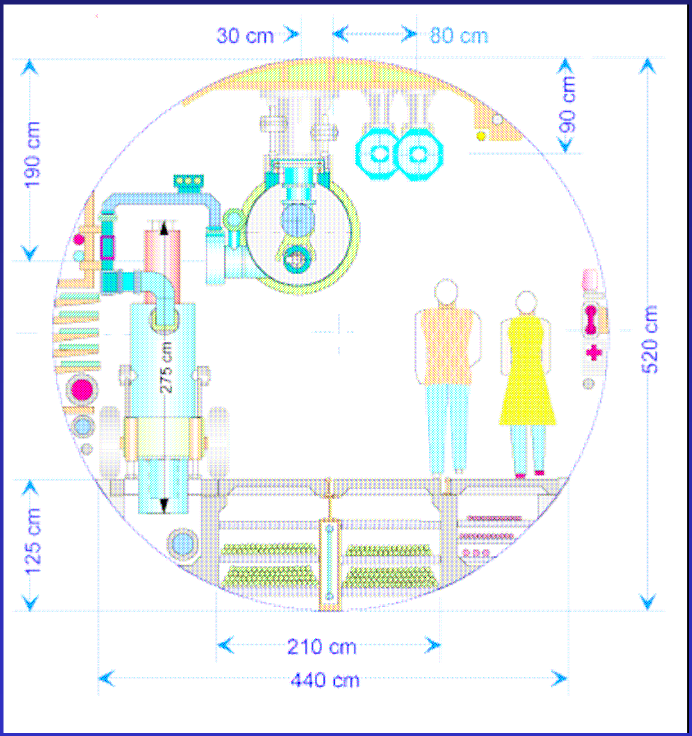
~30 km (500 GeV)

~50 km (1 TeV)



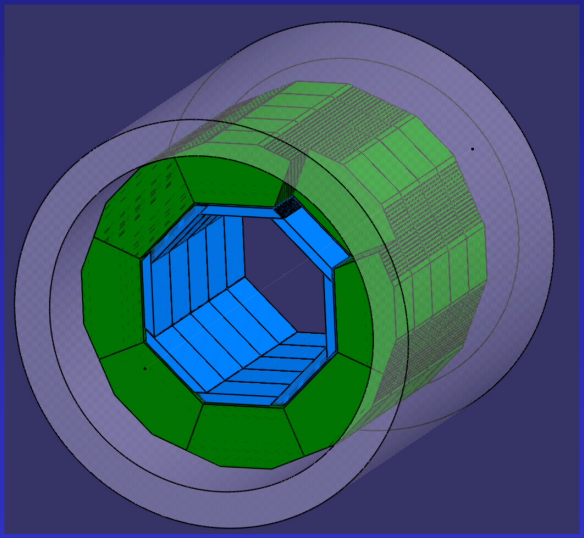
ILC Layout

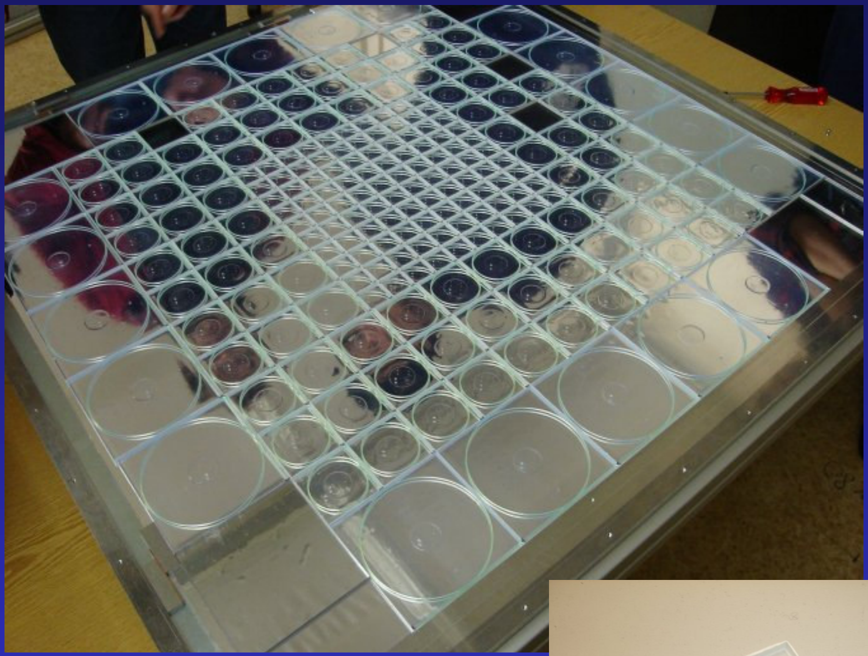

Typical Site Profiles Under Study

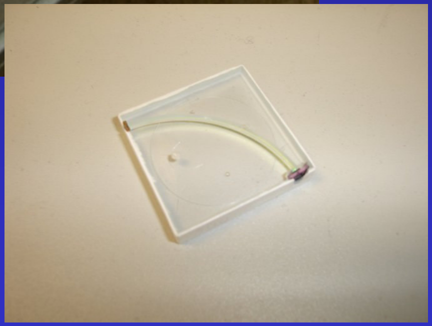


Silicon Photomultiplier Applications

- DESY International LInear Collider Group, in particularly Scintillator Tile Hadron Calorimeter Activity







Silicon photomultiplier readout of Scintillator Tile with WLS

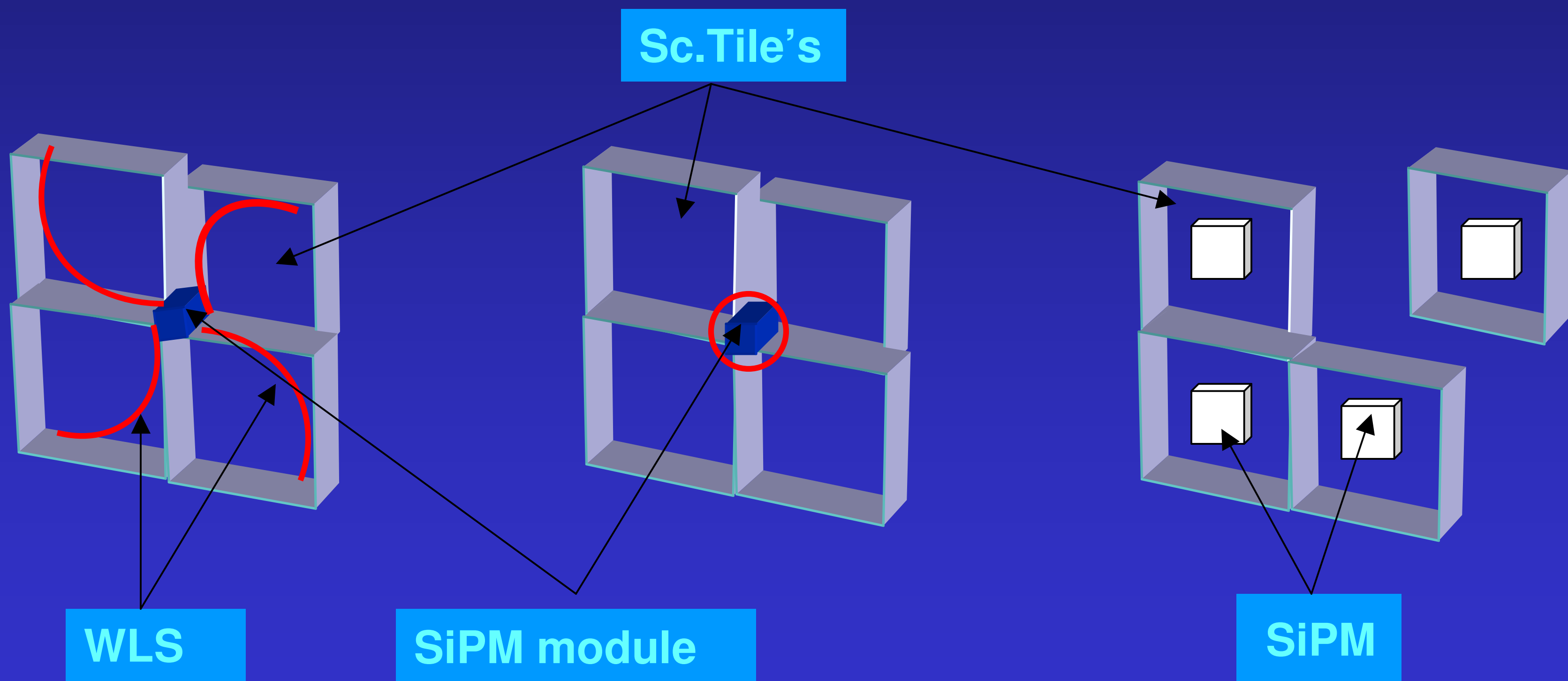
New R&D Project on the Photodetector for Hadron Scintillation Calorimetry

Main Goal: Direct Readout of Scintillation Tile of ILC Hadron Calorimeter by Silicon Photomultiplier

- Study of the Light Balance and Propagation in the Scintillation Tails for the ILC Hadron Calorimeter (Geant4 Simulation)
- Development of the Advance Silicon Photomultipliers
- Test setup for the Testing of the Scintillation Tail – Advance Silicon Photomultiplier
- Prototyping and Test of the Scintillation Tile - Silicon Photomultiplier Hadron Calorimeter Modules

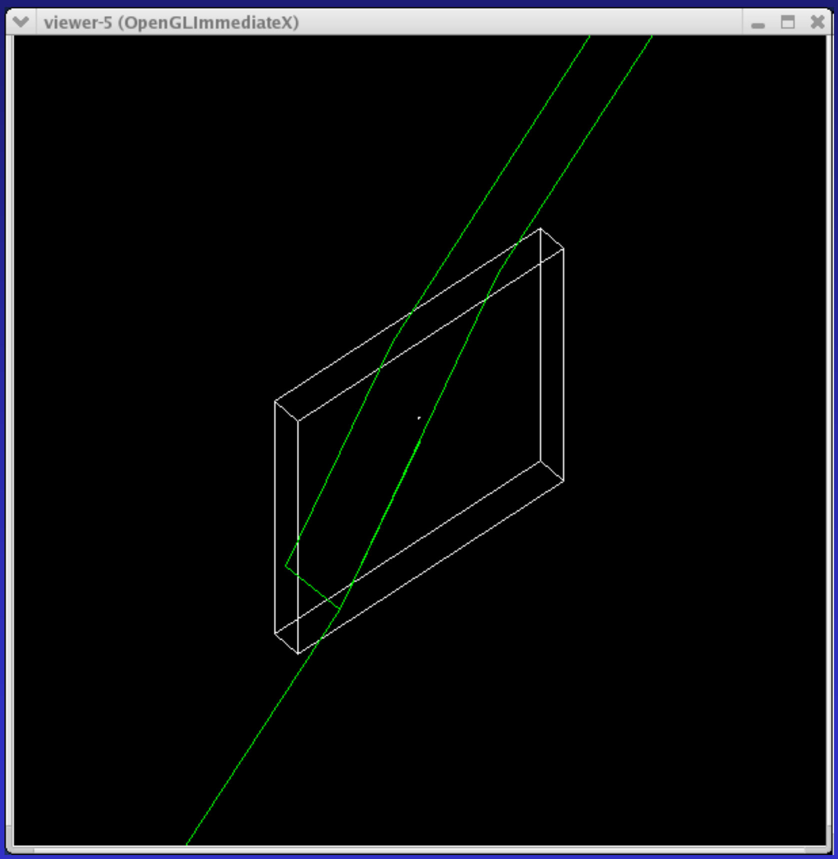
New R&D on the Photo Sensor/Scintillator

Main Goal: Direct Readout of Scintillation Tile of ILC Hadron Calorimeter by Silicon Photomultiplier



Simulation of the Tile/Photosensor Modules

GEANT_4, Optical Photons Interaction



Optical Photon Production:

- scintillation;
- Cherenkov Effect;

Optical Photon Interaction:

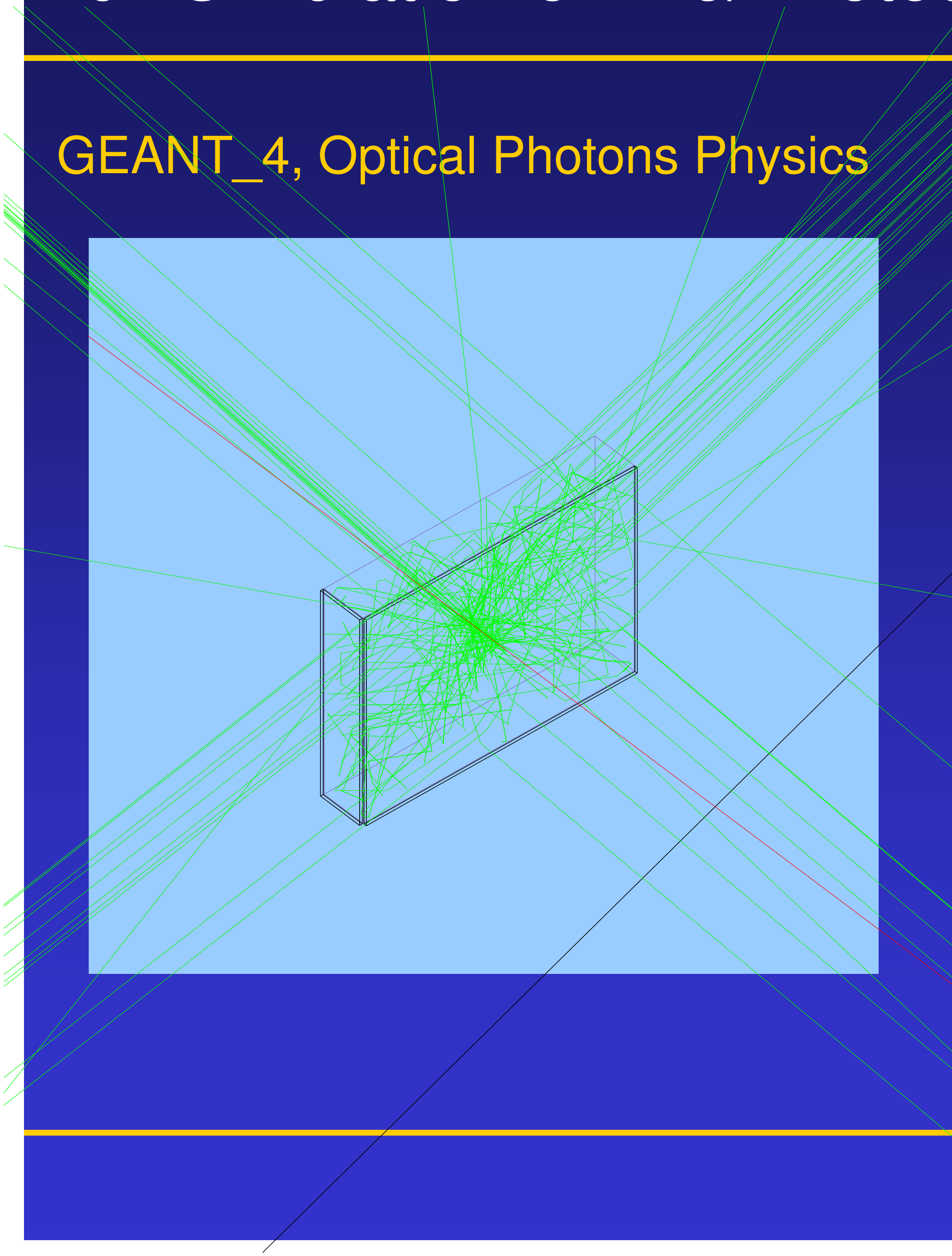
- elastic (Rayleigh) scattering;
- absorption
- medium Boundary Interactions.

Medium Boundary Effect:

- dielectric/dielectric;
- dielectric/metal;
- dielectric/black material

Full Simulation of Tile/Photodetector Module

GEANT_4, Optical Photons Physics

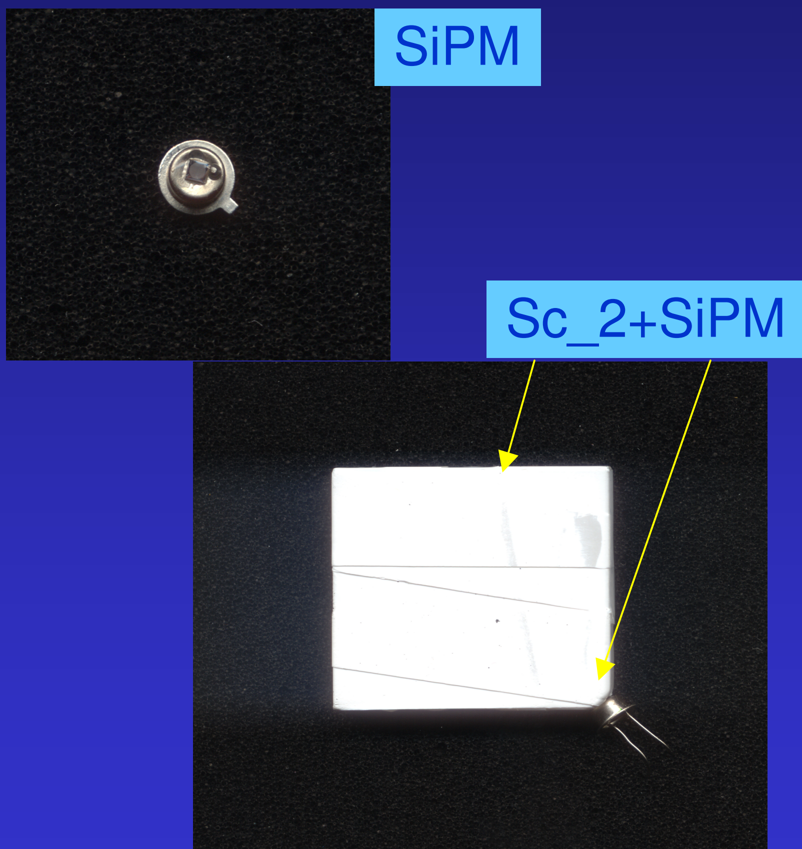


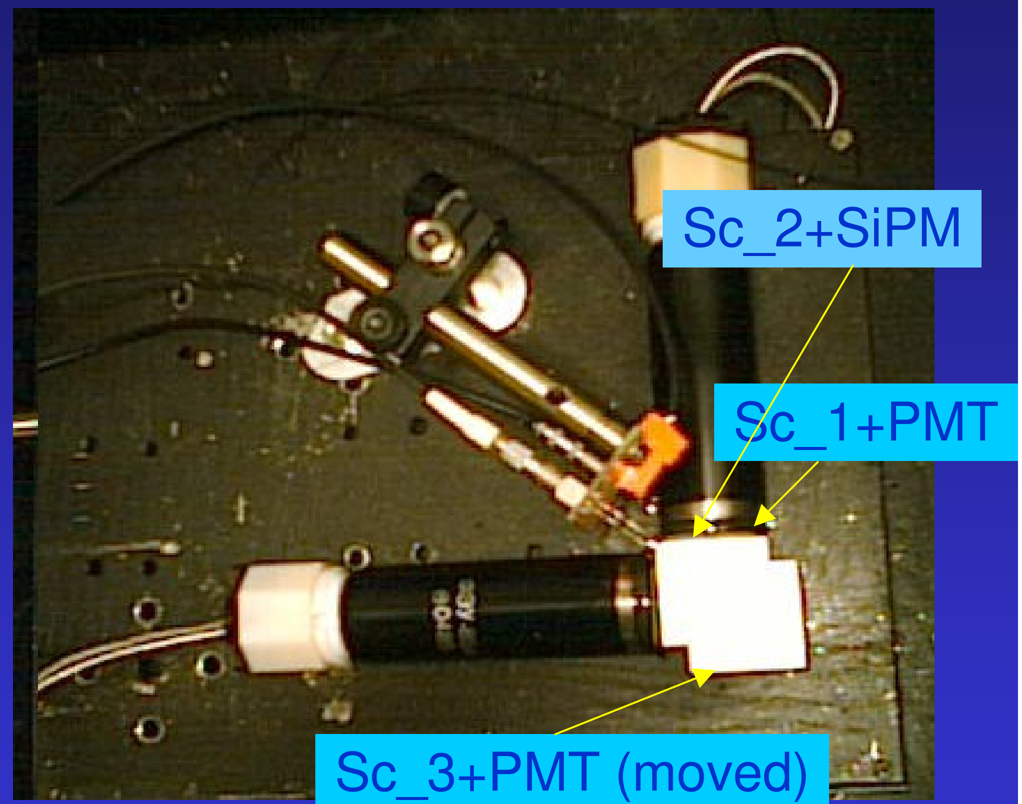
Full simulation of the Light propagation in the Scintillation Tile/Photodetector Module

6 GeV muons cross the tile
1/100 of intensity of created photons

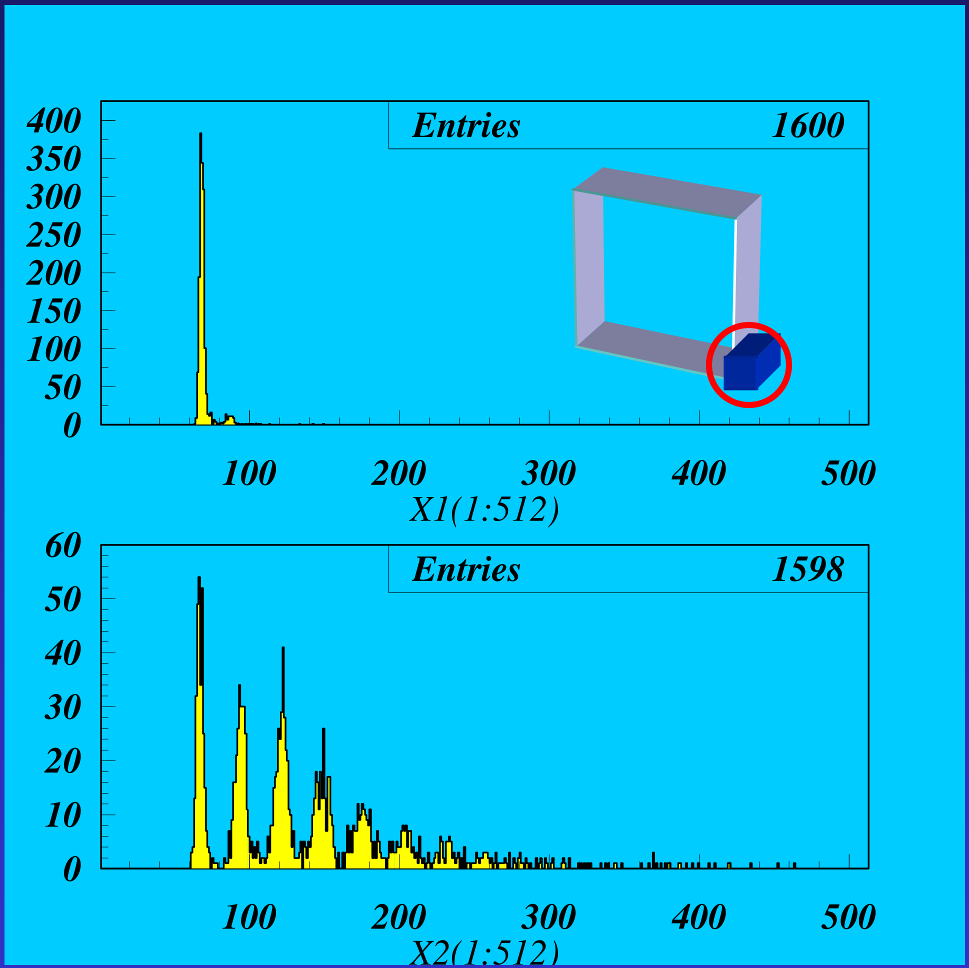
Direct Measurement of Light Out by Silicon Photomultiplier

The direct measurements of the Light output from Plastic Scintillation Tiles by SiPM – Test Setup – Cosmic Muons Telescope





Direct Measurement of Light Out by Silicon Photomultiplier



Direct Readout of

Scintillation Tile (3x3 cm, 5mm) with Teflon Reflectors by SiPM (CPTA Moscow) 1x1 mm

Cosmic Muons

Efficiency of registration of MIP is 80%

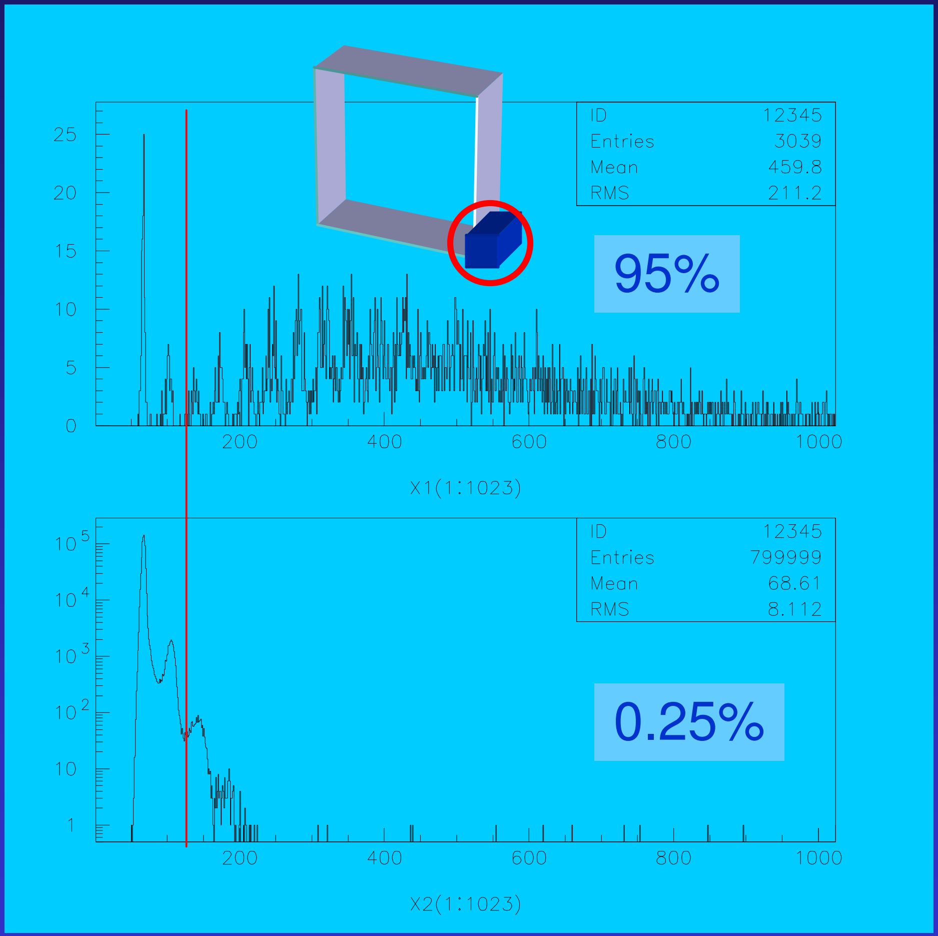
Mean value is 1.8 of photoelectrons/mip (from Poisson Distribution)

Direct Measurement of Light Out by Silicon Photomultiplier

Two main direction:

1. Increasing the sensitive area of Silicon Photomultiplier
2. Increasing sensitivity to blue region of light

Direct Measurement of Light Out by Silicon Photomultiplier



Direct Readout of

Scintillation Tile (3x3 cm, 5mm) with Teflon Reflectors by MCP (SiPM HAMAMATSU) 1x1 mm

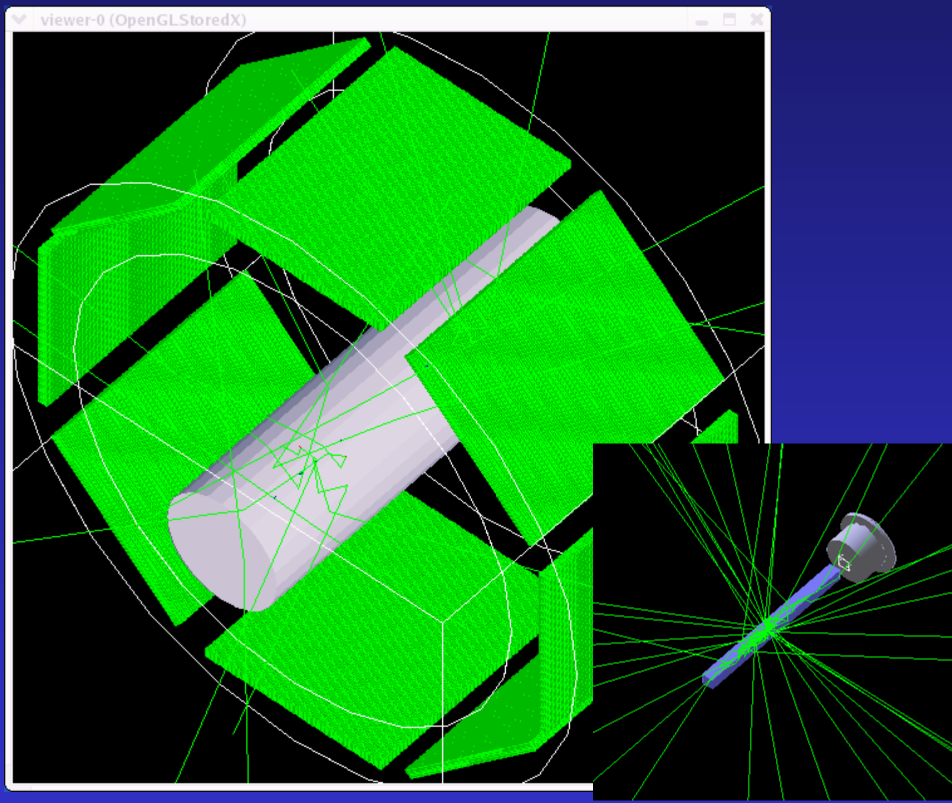
Cosmic Muons

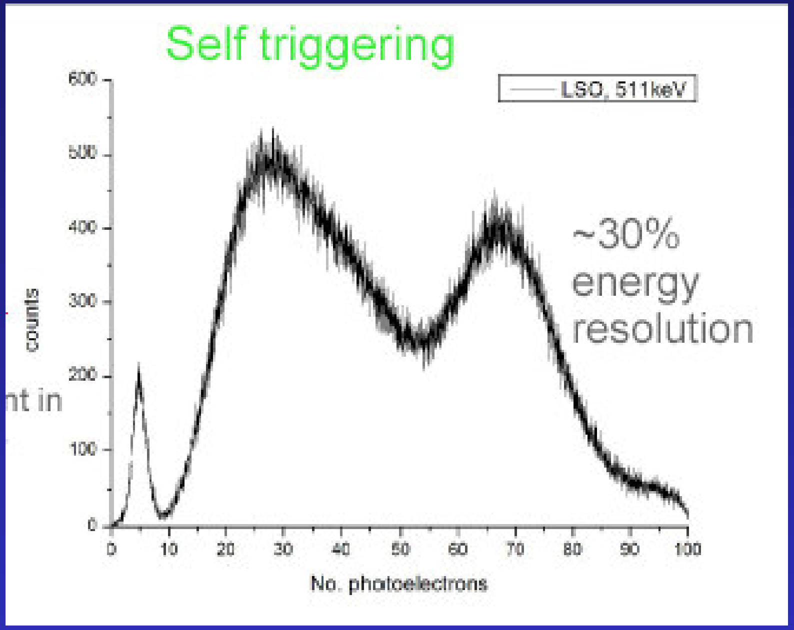
Efficiency of registration of MIP is 95%

Mean value is 12 of photoelectrons/mip

Silicon Photomultiplier Applications

- Positron Emission Tomography



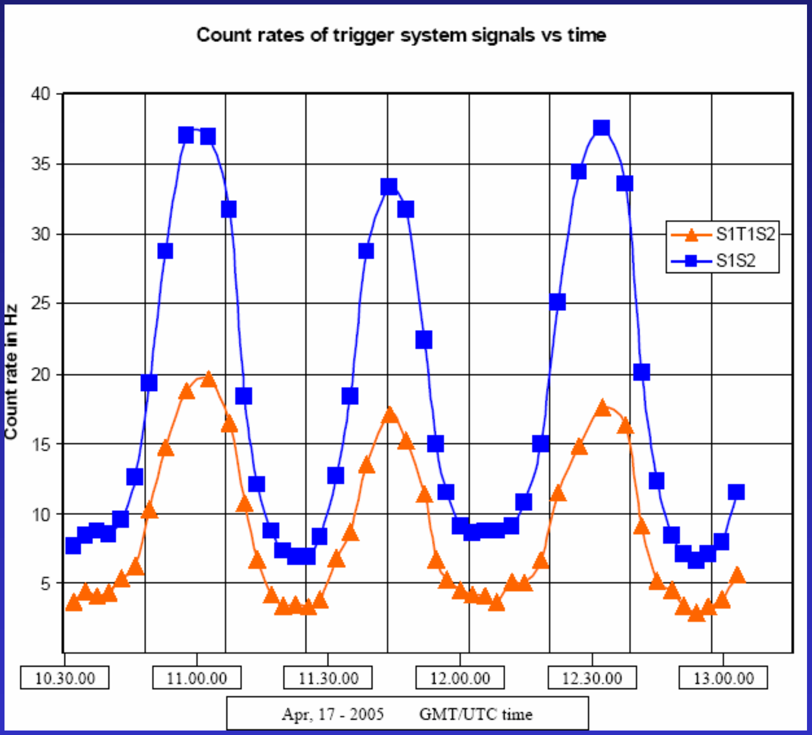


Spectrums of 22Na (511 keV) with LSO

Silicon Photomultiplier is most promising Photodetector for the Modern Scintillator Material and Medical Imaging Systems

Silicon Photomultiplier Applications

- SiPM in space



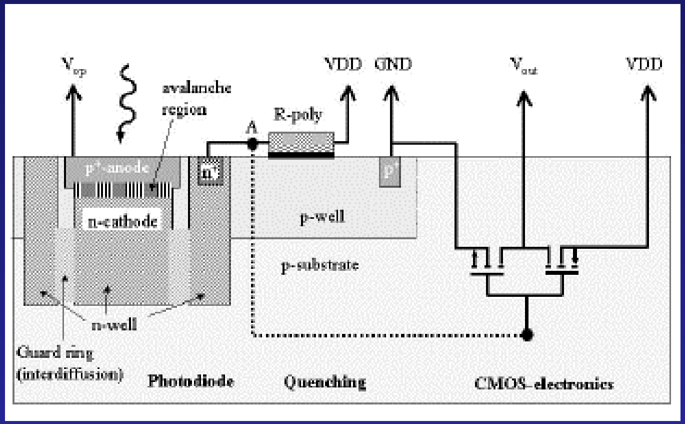
Silicon Photomultiplier is most promising Photodetector for the space applicatioin

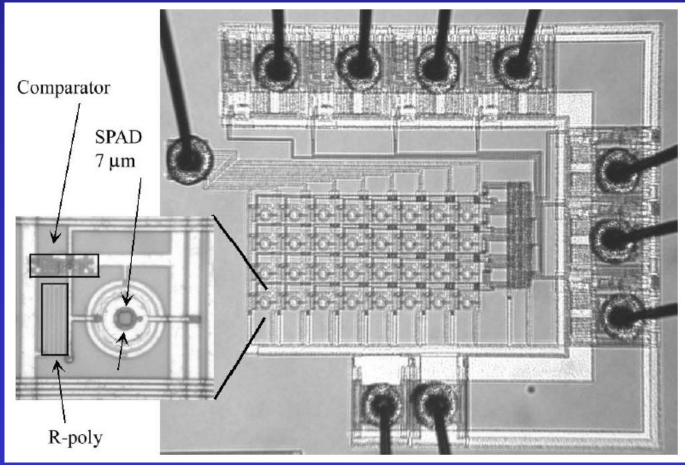
Silicon Photomultiplier: Near Future Efforts

- Large Size of Photomultiplier
  - 2x2 mm, 3x3 mm, … 10x10 mm ?
- Matrix of Silicon Photomultipliers
  - No limitation of sensitive area
- Combination of Sensor and Electronics
  - Technology is sufficient for this

Silicon Photomultiplier: Future Development

- Combination of Sensor and Electronics
  - Technology is sufficient for the integration of the Silicon Photomultiplier and Front end electronics





Combining the sensor part with frontend electronics in the same technology is future

Conclusion

Silicon Photomultiplier is the novel photodetector which can be consider as substitution to the convention PMT in many applications